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Climate sensitivity: model dependence of results.

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Climate Sensitivity: Model dependence of results

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Abstract

There has been an increasing use of numerical models over the last 20 years to study climatic change. The simulated sensitivity of climate to a given perturbation is dependent on the model used. This dependence is illustrated using examples from numerical studies of the effect of increasing atmospheric carbon dioxide concentrations. The parametrization of cloud and the land surface and the modelling of the oceans, which give rise to the current major uncertainties in determining climate change, will be the focus of numerical modellers' attention over the next decade.

1. INTRODUCTION

Considerable interest in the understanding and prediction of climate change has been maintained over the last 15 years. There has been a gradual shift in emphasis from changes due to natural perturbations (for example due to variations in the atmosphere's turbidity due to volcanic eruptions, or changes in the solar constant) to potential changes due to man's activities (for example those leading to increased concentrations of radiatively active gases). The prediction of the climatic effects of increased carbon dioxide concentrations requires the solution of many of the problems inherent in predicting climate change in general. Thus, in this paper, examples of model dependence of climate sensitivity will be drawn from studies of the effect of increased CO_2 carried out over the last decade or so.

Attempts to predict the climatic effects of doubling CO_2 from globally averaged models have produced a wide range of results, giving surface temperature increases ranging from 0.2K (Newell and Dopplick, 1979) to 9.6K (Moller, 1963). Schneider (1975) attempted to clarify the reasons for the discrepancies between some of the earlier results, noting the dependence on the assumptions made and the models used. More recently, there have been a number of studies using 3-dimensional general circulation models (GCMs) producing estimates of equilibrium surface warming from 1.3K (Washington and Meehl, 1983) to 5.2K (Wilson and Mitchell, 1987) for doubling CO_2, and large variations in the simulated geographical changes in climate (Dickinson, 1986;

Schlesinger and Mitchell, 1987). The possible reasons for discrepancies between recent GCM studies will form the subject of this paper, since this is a topic in which the author has a special interest. See Schlesinger (1985) for a comprehensive discussion of studies of the effects of increased CO_2 using radiative-convective models.

We begin this review of GCM sensitivity studies in the following section by considering a hierarchy of experiments carried out by Manabe and his co-workers at the Geophysical Fluid Dynamics Laboratory at Princeton (GFDL). The strength of selected feedback processes is assessed in Section 3, and the importance of using a model which produces a faithful representation of current climate is stressed in Section 4. In Section 5, the dependence of climate sensitivity on the choice of physical parametrization is illustrated using two examples, and the final section comprises a summary and some concluding remarks.

2. A HIERARCHY OF GENERAL CIRCULATION EXPERIMENTS ON THE EFFECT OF INCREASED CO_2

The first study of the effect of doubling atmospheric CO_2 using a GCM model was carried out at GFDL by Manabe and Wetherald (1975). This formed the first of a series of experiments in which increasingly realistic (and more complex) versions of the model were used in order to isolate the effect of various features on climate sensitivity. To enable a rough comparison of the different experiments, it will be assumed that the global mean temperature change on doubling atmospheric CO_2 concentrations is half that due to quadrupling CO_2 (see Augustsson and Ramanathan, 1977).

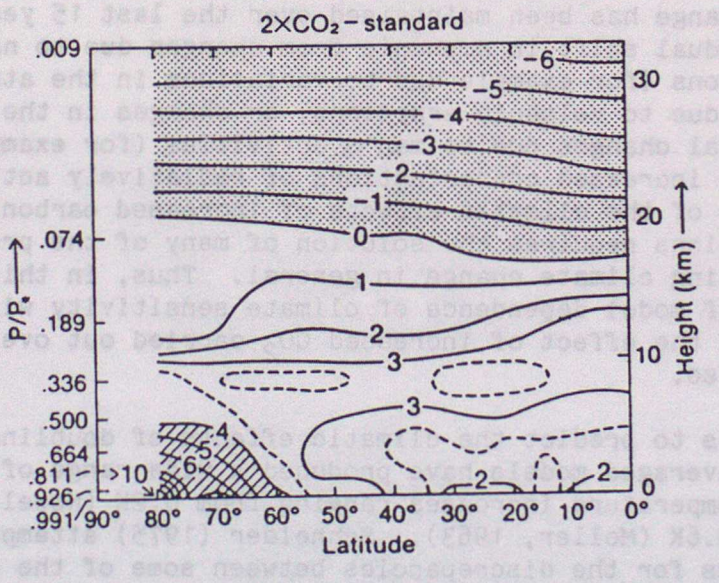

Figure 1 Height-latitude diagram of the zonally averaged temperature changes (K) due to doubling CO_2 in an idealized climate model (from Manabe and Wetherald, 1975).

Table 1

Global mean surface temperature change due to doubling atmospheric CO_2 amounts in GFDL experiments. Figures in brackets are obtained by halving the result for quadrupling CO_2. The second column of figures contains results using a revised radiation scheme.

Model.	Temperature Change	
1-D radiative convective	2.4	2.0
Annual mean sector	2.9	
Annual mean sector (variable cloud)		3.0
Mixed layer models		
Annual mean, sector		(3.0)
Seasonally varying, sector		(2.4)
Seasonally varying, realistic geography (1)		(2.0)
Seasonally varying, realistic geography (2)		3.2
Seasonally varying, realistic geography (variable cloud) (3)		4.0

Footnotes (1) Manabe and Stouffer (1980), using climatological zonally averaged cloud.

(2) Wetherald and Manabe (1988), using prescribed cloud derived from the control simulation in (3). This differs from the cloud distribution in (1), giving different sea temperatures and sea-ice extents in the control simulation, and hence a different sensitivity to doubling CO_2.

(3) Wetherald and Manabe (1988), using the same model as in (2).

In the original GFDL experiment (Manabe and Wetherald, 1975), orography and the seasonal variation of insolation were ignored. The domain was restricted to a sector of the globe with an idealized land-sea distribution. The ocean was treated as a 'swamp', having no heat capacity or heat transport. Cloud amounts were prescribed. Doubling CO_2 concentrations produced a warming of 2.9K (Table 1).

This is somewhat larger than the 2.4K found using a radiative convective model (Manabe and Wetherald, 1967) presumably due to the large amplification of the warming in high latitudes obtained in the GCM (Figure 1).

Manabe and Wetherald attributed the polar amplification of the warming to temperature-albedo feedback, enhanced poleward transport of latent heat and the confinement of the warming to low levels under the strong polar inversion. The warming in the tropics is less than that found using the radiative convective model, which assumes a fixed 6.5K/km lapse rate. The moist convective parametrization used in the GCM

adjusts the lapse rate towards the moist adiabatic, enhancing the warming in the upper troposphere and reducing it at the surface (see for example, Rowntree and Walker, 1978).

The 'swamp' model was modified to include a prognostic cloud scheme (Manabe and Wetherald, 1980). On increasing atmospheric CO_2 amounts there was a general decrease in middle and upper tropospheric cloud especially in convective regions, reducing reflected solar radiation and enhancing the radiative warming. However, as the mean cloud height in the tropics was also reduced, the effective emission temperature increased, enhancing thermal emission and almost compensating the solar effect. Low cloud also increased, particularly in high latitudes. However, because incoming insolation is small in these regions, the resulting increase in reflected insolation is again almost compensated by the corresponding reduction in thermal emission. Thus the global mean warming for a given increase in CO_2 concentrations was similar in the two models. It appeared from this experiment and a parallel study investigating the effect of changes in the solar constant (Wetherald and Manabe, 1980) that changes in cloud cover contributed little to climate sensitivity.

In order to include a seasonal cycle, Wetherald and Manabe (1981) replaced the 'swamp' model ocean with a 68 m 'mixed-layer' ocean in which cloud cover was prescribed and oceanic heat transport was still ignored. Two experiments were carried out in which CO_2 amounts were quadrupled - in the first, annual mean insolation was prescribed, and in the second, the full seasonal variation of insolation was included. The implied warming for a doubling of CO_2 was smaller in the case of the seasonal model (Table 1). The seasonal model produced a warmer control climate and hence less snow cover and a smaller temperature albedo feedback. In addition, the temperature albedo feedback in the seasonal model is probably smaller because in summer the albedo feedback is minimal since although insolation is at a maximum, snow and sea-ice extents are very small. When the sector is replaced by realistic geography and orography (Manabe and Stouffer, 1980), the global warming is reduced still further (Table 1). The lack of temperature albedo feedback over Antarctica, which arises as temperatures do not exceed freezing even in the enhanced CO_2 simulations, and the underestimation of southern hemisphere sea-ice extents both may contribute to the reduced sensitivity in this model.

A comparison of the earlier GFDL experiments with this study demonstrates that simplified models may give results which are qualitatively similar to those in a more detailed model, but are quantitatively inaccurate. Unfortunately, simplification may lead to qualitative differences, as a subsequent GFDL experiment showed.

Wetherald and Manabe (1988) studied the effect of doubling CO_2 amounts in a revised version of Manabe and Stouffer's (1980) model with both prescribed and predicted cloud. The changes in surface

temperature were 3.2K and 4.0K respectively (Table 1), in contrast to the earlier "swamp" model experiments which indicated that changes in cloud did not affect climate sensitivity. In the more recent experiment, there were pronounced increases in high cloud in the tropics in addition to the decreases in middle and upper tropospheric cloud found with the "swamp" model. The associated increase in reflected insolation was small because high cloud has a low albedo, but the reduction in outgoing thermal emission was large, leading to a substantial positive feedback. In the earlier experiment, the model level nearest to the tropical tropopause was at 70 mb where changes in cloud were small, whereas in the later experiment, the vertical distribution of levels was changed, giving a level at 95 mb, corresponding to the maximum increase in cloud (Wetherald, 1988, personal communication). In addition, the increases in low cloud are smaller in the seasonal model, enhancing the overall positive feedback process of cloud cover (Wetherald and Manabe, 1988).

3. ANALYSIS OF FEEDBACKS

It is clear from the above experiments that changes in sea-ice and cloud amounts enhance the simulated response to increases in atmospheric CO_2. In order to quantify the contributions due to changes in individual parameters, Hansen et al. (1984) carried out an analysis of feedbacks in three climate change experiments. The feedback strengths, assumed to be linear, were estimated by inserting globally averaged changes from the three-dimensional climate model in a one-dimensional radiative-convective model. Following Hansen's analysis

$$\Delta T_{eq} = \Delta T_o \, (1-\sum g_i)^{-1} \qquad (1)$$

Where ΔT_o is the equilibrium temperature change due to doubling CO_2 in the absence of feedbacks, g_i are the 'gain factors' associated with individual feedbacks, and ΔT_{eq} is the equilibrium temperature change with all the feedbacks included. The gain factors associated with changes in water vapour, surface albedo and cloud (g_w, g_s and g_c respectively) from the Hansen et al. (1984) experiments are shown in Table 2.

Table 2

Gain factors from Hansen et al, (1984) derived from simulations with doubled CO_2 amounts

	Standard	Using model with enhanced sea-ice extents
Water vapour	0.40	0.37
Surface albedo	0.09	0.12
Cloud	0.22	0.26

The largest gain factor (and hence the strongest feedback) is due to changes in water vapour: the next strongest is due to changes in cloud cover. The second column of Table 2 shows results from 2 xCO_2 experiment carried out using a version of the model with a greater area of sea ice in the unperturbed simulations, leading to a stronger temperature-albedo feedback.

Although the 'gain factors' are additive, the associated amplification is highly non-linear (Table 3).

Table 3

Cumulative warming on doubling CO_2 amounts on adding selected feedback processes (Hansen et al, 1984).

No feedback	1.2
Water vapour	2.0
Water vapour, surface albedo	2.4
Water vapour, surface albedo, cloud	4.2

The estimated warming including water-vapour feedback (Table 3) is compatible with the revised GFDL radiative-convective calculation (Table 1, top line), and that with water vapour, surface albedo and cloud feedback is compatible with the full GFDL model (Table 1, bottom line)

It is possible that a warmer climate would be accompanied by an increase in the water content of clouds, and hence a change in cloud radiative properties. Somerville and Remer (1984) speculated that this would produce a strong negative feedback, though this was not apparent in numerical simulations carried out by Roeckner et al, (1987). A further cloud feedback due to changes in cloud condensation nuclei has been postulated (Charlson et al. 1987). For detailed discussions of climate feedback processes see Dickinson (1986) and Schlesinger (1985).

4. IMPORTANCE OF THE SIMULATED CONTROL CLIMATE

We have seen in the preceding section that Hansen et al, (1984) found enhanced climate sensitivity when their model was altered to give greater sea-ice coverage in the control simulation. This change in sensitivity is particularly noticeable in results from a set of experiments reported by Spelman and Manabe (1984). Three versions of their model were used, differing only in the treatment of the oceans and the specification of the solar constant. The global mean temperature in the unperturbed simulation ranged from 278K to 288K and the sensitivity to quadrupling CO_2 varied by a factor of over 2 (Figure 2).

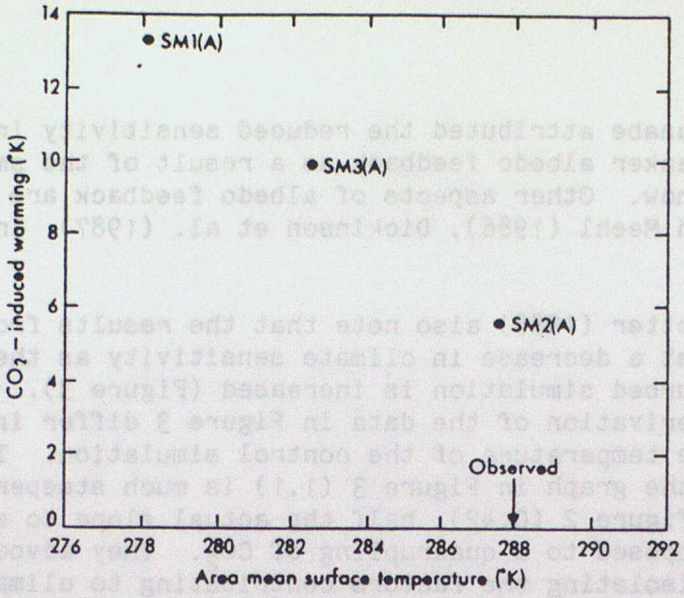

Figure 2 Relationship between an idealized 3-dimensional climate model's sensitivity to a quadrupling of CO_2 and the simulated control temperature. (From Spelman and Manabe, 1984)

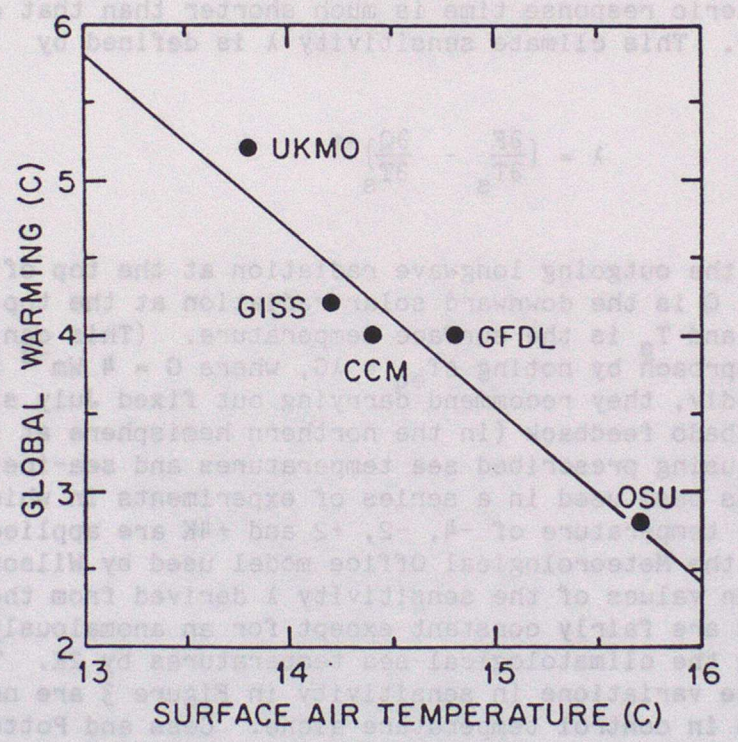

Figure 3 Global mean surface warming due to doubling CO_2 as a function of the mean surface temperature from five GCM experiments, UKMO, Wilson and Mitchell (1987); GISS, Hansen et al. (1984); NCAR, revised estimate based on Washington and Meehl (1984); GFDL, Manabe and Wetherald (1987); OSU, Schlesinger and Zao (1987).

Spelman and Manabe attributed the reduced sensitivity in the warmer models to a weaker albedo feedback as a result of the smaller area of sea-ice and snow. Other aspects of albedo feedback are discussed by Washington and Meehl (1986), Dickinson et al. (1987), Ingram et al. (1989).

Cess and Potter (1988) also note that the results from recent CO_2 studies suggest a decrease in climate sensitivity as the temperature of the unperturbed simulation is increased (Figure 3). The models used in the derivation of the data in Figure 3 differ in many ways other than the temperature of the control simulation. This may be why the slope of the graph in Figure 3 (1.1) is much steeper than that deduced from Figure 2 (0.42), half the actual slope to allow for a doubling as opposed to a quadrupling of CO_2. They advocate various measures for isolating the factors contributing to climate sensitivity. First, instead of applying a radiative perturbation, such as that due to doubling CO_2 amounts, and using the resultant change in surface temperature as a means of determining climate sensitivity, they propose prescribing a surface temperature perturbation, and using the resulting change in radiative fluxes to determine climate sensitivity. This requires less computing power as the atmospheric response time is much shorter than that of the ocean mixed layer. This climate sensitivity λ is defined by

$$\lambda = \left(\frac{\partial F}{\partial T_s} - \frac{\partial Q}{\partial T_s}\right)^{-1}$$

where F is the outgoing longwave radiation at the top of the atmosphere, Q is the downward solar radiation at the top of the atmosphere and T_s is the surface temperature. (This can be related to Hansen's approach by noting $\Delta T_{eq} = \lambda G$, where $G = 4\ Wm^{-2}$ for doubling CO_2.) Secondly, they recommend carrying out fixed July simulations so that the albedo feedback (in the northern hemisphere at least) is minimised, using prescribed sea temperatures and sea-ice extents. This approach has been used in a series of experiments in which changes in sea surface temperature of -4, -2, +2 and +4K are applied in the version of the Meteorological Office model used by Wilson and Mitchell (1987). The values of the sensitivity λ derived from these experiments are fairly constant except for an anomalously high value on reducing the climatological sea temperatures by 2K. Thus, as noted earlier, the variations in sensitivity in Figure 3 are not due to differences in control temperature alone. Cess and Potter (1988), for example, find that the value of λ estimated from their model is very sensitive to the specification of cloud albedo.

Manabe and Bryan (1985), using a coupled ocean atmosphere model with seasonal mean insolation and realistic geography, demonstrated

that changes in ocean circulation can also alter λ. With successive increases in CO_2 concentrations above present day values, they found little change in the oceanic meridional circulation or in climate sensitivity. However, with reductions in CO_2 amounts below the current level, there was a substantial weakening of the thermohaline circulation and a marked rise in climate sensitivity. This study emphasises the importance of including changes in oceanic circulation as well as using a model which produces an accurate simulation of present day climate.

In this section we have emphasised the dependence of global climate sensitivity on the control climate. Obviously, the prediction of regional climate change will depend on the accuracy of the simulation of present day regional climate, as has been demonstrated by Palmer and Mansfield (1986), and Mitchell et al. (1987).

5. DEPENDENCE ON PHYSICAL PARAMETRIZATIONS

We have seen in Section 3 that changes in cloud can enhance climate sensitivity. The use of alternative parametrizations may alter the simulation of present day climate which will also affect climate sensitivity, as seen in the previous section. Thus altering or adding a parametrization of a physical process can alter climate sensitivity directly (for example, by introducing an additional feedback) and indirectly through altering the climate of the control simulation. The indirect effects should be allowed for when analysing sensitivity experiments. Here, we consider two aspects of simulated climate change induced by enhancing atmospheric CO_2.

5.1 Amplification of the warming with height in low latitudes.

Numerical studies of the effect of doubling atmospheric CO_2 differ in the vertical profile of the warming in the tropics. (Schlesinger and Mitchell, 1987; Wilson and Mitchell, 1987). In studies using a moist convective adjustment scheme (Washington and Meehl, 1984; Wetherald, and Manabe 1988) the maximum warming in the tropical troposphere is 3 to 4K, less than twice the surface warming. In studies using a penetrative scheme (Hansen et al, 1984; Wilson and Mitchell, 1987), the upper tropospheric warming reaches 7 to 8K and is substantially greater than twice the surface warming. Thus it appears that the characteristics of the warming in the tropics are dependent on the convective parametrization. In order to isolate the effect of changing the convective parametrization, Cunnington and Mitchell (1989) have carried out two sensitivity studies in which CO_2 concentrations were doubled, and sea surface temperatures were everywhere increased by 2K. The first study used a penetrative convection scheme, the second a non-penetrative scheme (not moist convective adjustment). The upper tropospheric warming was about 1K greater in the experiment with the penetrative scheme (Figure 4) as this is more efficient in moving heat and moisture from the boundary layer to upper layers. The associated decrease in upper

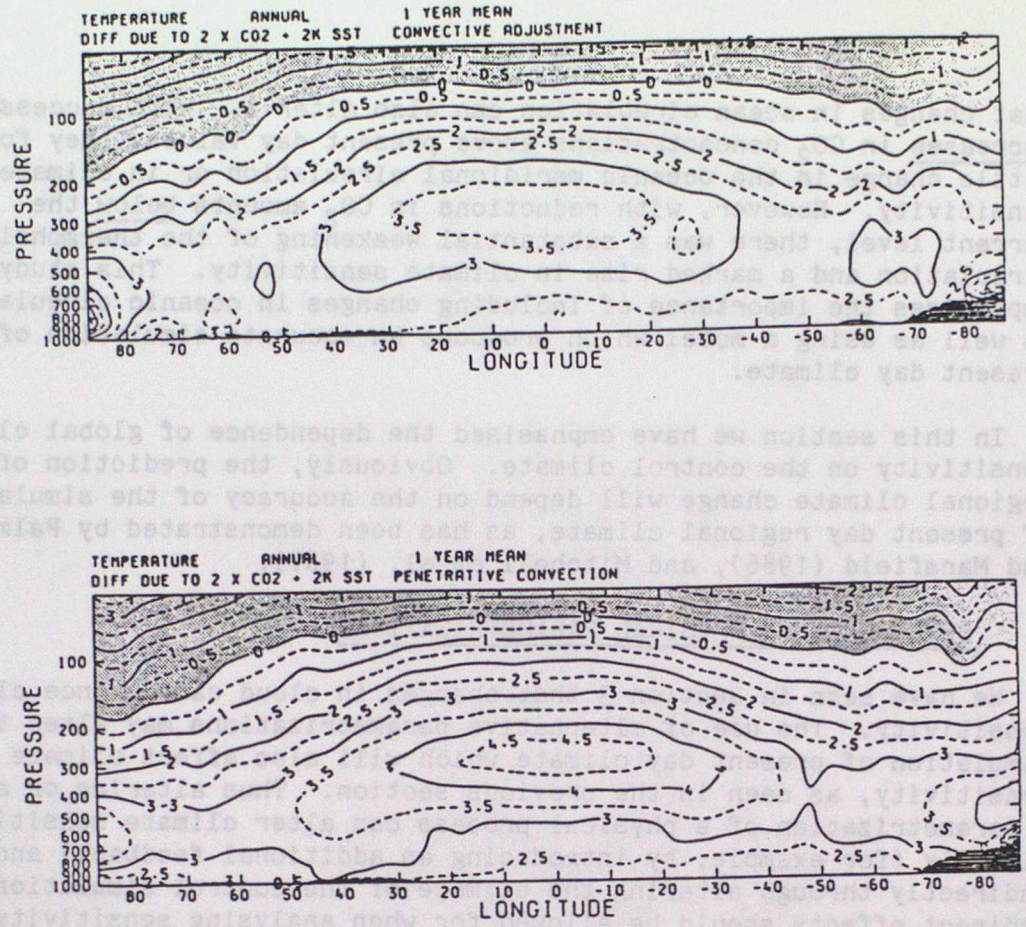

Figure 4 Changes in zonally averaged temperature (K) due to doubling CO_2 and enhancing sea surface temperatures by 2K.

(a) Using a non-penetrative convection scheme.

(b) Using a penetrative scheme.

(from Cunnington and Mitchell, 1989).

tropospheric cloud, and increase in cloud around the tropopause (not shown) is also more pronounced with the penetrative scheme as found in earlier CO_2 studies.

The surface warming in the tropics due to doubling CO_2 is also greater in models using a penetrative scheme (Hansen et al, 1984; Wilson and Mitchell, 1987) than in those using a non-penetrative convection scheme. The reverse is true in radiative-convective models

using prescribed cloud amounts (for example, see Schlesinger 1985), where the penetrative schemes, being more efficient in transporting heat upwards, give a greater warming in the upper troposphere and a smaller warming of the surface on doubling CO_2. Note that in the GCM experiments, the increases in high cloud and reductions in middle and upper tropospheric cloud are larger in models with a penetrative scheme, indicating that the positive cloud feedback may be larger in these models and accounting for the apparent discrepancy with the radiative-convective model experiments.

5.2 Summer drying of northern mid-latitudes

Many equilibrium studies of the effect of increasing CO_2 suggest a drying of the northern extra tropical land surface in summer (Manabe et al, 1981; Mitchell, 1986; Manabe and Wetherald, 1987; Wilson and Mitchell, 1987; Schlesinger and Zao, 1987). On the other hand Hansen et al (1984) report substantial areas of increased soil wetness, and Washington and Meehl (1984) find a general moistening of the northern continents in summer with increased CO_2. Manabe et al. (1981) attributed the summer drying to enhanced evaporation, earlier snowmelt especially in more northerly latitudes and, in some areas, reduced precipitation. It also appears that in order to produce a drying,the soil should be close to saturation in early spring in the unperturbed simulation, so that the enhanced precipitation during the winter found on enhancing CO_2 concentrations is run off during snowmelt and not accumulated in the ground (see Figure 5, from Mitchell and Warrilow, 1987).

If the spring soil moisture in the unperturbed climate is reduced well below the runoff threshold, for example by running off snowmelt and rain if the sub-surface soil layers are frozen, then the enhanced rainfall in autumn and winter in the warmer enhanced CO_2 simulation is accumulated in the soil. Thus the drying out of the soil in spring starts from a higher level than in the control (Figure 5b) and the land surface is wetter for much of the summer with enhanced CO_2. This may explain why the model of Hansen et al. (1984), which allows for enhanced runoff if the ground is frozen, does not produce a widespread summer drying. Meehl and Washington (1988) note that in their model (Washington and Meehl, 1984) the soil is below saturation at most grid points throughout the year in the control simulation, and so the land surface generally becomes wetter in northern mid latitudes in summer on doubling CO_2. They attribute the dryness of the land surface in their control simulation to unrealistically low values of surface albedo over land which elevate the rates of evaporation.

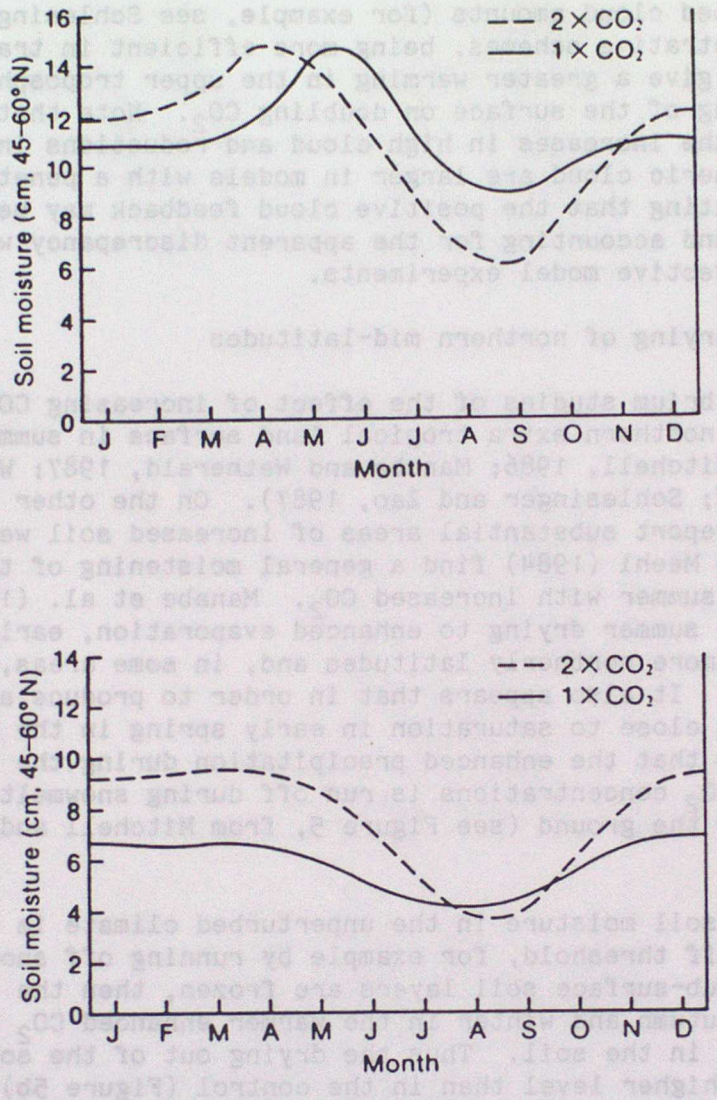

Figure 5 Soil moisture (cm, averaged over 45-60°N) in 1 and 2 x CO_2 simulations.

(a) With standard runoff parametrization

(b) With snowmelt and rain runoff over frozen ground.

(from Mitchell and Warrilow, 1987).

6. CONCLUDING REMARKS

In the preceding sections, we have identified various factors influencing climate sensitivity. These include

1) Climatic feedbacks including those involving cloud and sea-ice.

2) Dependence on the control simulation, especially on temperature.

3) The model domain (eg sector or realistic geography).

4) The physical parametrization (eg of convection or land surface processes).

There are still many differences between existing comparable studies of the effects of increasing CO_2 which are yet to be explained. For example, Rind (1987) has considered the influence of changes in the meridional gradient of sea surface temperature, but does not attempt to explain why the change varies from model to model. We are still at the stage of identifying mechanisms of climate change as opposed to providing quantitative estimates of regional changes.

Over the next few years, research will continue to be directed towards identifying those processes which are critical in determining climate sensitivity, and to removing current uncertainties. Topics which are of particular interest include:

1) The influence of clouds and climate. There is a requirement for observational studies of cloud to provide data on which to base the parametrization of cloud, including cloud radiative properties, in atmospheric models. This is at present an area of major uncertainty.

2) Little as yet is known about the likely response of the oceanic circulation to climatic perturbations. The continuing increase in computing power over the next decade will enable climate simulations of a century or more using detailed coupled dynamical models of the atmosphere and ocean. There is much to be learnt concerning the importance of the parametrization of deep convection, the seasonal mixed layer and sea-ice in determining the performance and sensitivity of such models. Coupled models will enable an evaluation of the transient as well as the equilibrium response to climate perturbations.

3) To date, most GCMs have not attempted to model the effects of vegetation. Sellers et al. (1986) and Dickinson (1984) have developed complex models of the land surface (including vegetation) which have been incorporated in GCMs but have not yet been used in climate studies. It remains to be seen whether or not vegetation changes are likely to modify climate change, and if the most recent parametrizations are adequate.

4) Most simulations of the effect of enhanced CO_2 to date have used relatively low horizontal resolution (typically 15 spectral waves or the finite difference equivalent). There is a need to use models with higher resolution in both the horizontal and the vertical to improve the simulation of present day mean climate and climatic variability.

5) There are many other aspects of climate models which require improvement. Although it is not always possible to distinguish which of two parametrizations is the more suitable (as for example with the case of non-penetrative and penetrative convection schemes), the increasing availability of satellite data and operational forecasting analyses will provide an opportunity for a more careful validation of simulations of present day climate.

As climate models become more complex, it is possible that the simulated response to imposed perturbations may become more diverse. The additional complexity will make it more difficult to unravel the reasons for the diversity in response. If one is to have confidence in numerical predictions of climate change, then the reasons for discrepancies in the simulated response must be understood, and if possible eliminated. Ideally, one would aim to perfect all aspects of the model, but in a world with limited resources, this is not possible. However, by carrying out carefully designed sensitivity experiments, it may be possible to identify those processes which are critical. Scientific effort can then be concentrated on developing accurate physically based representations of these critical processes which in turn will reduce the uncertainties in simulated climate change. This will be a continuing theme of climate research over the next decade.

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